

SUMMARY of RESEARCH

For Grant NAG5-10435 of the NASA Planetary Astronomy Program

"GROUND BASED STUDIES of the OUTER PLANETS"

for 3/1/2001 to 2/28/2005

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Introduction

This report covers progress to date under this grant on our continuing program to conduct ground based studies of the outer solar system planets and satellites, with emphasis on spectroscopy and atmospheric phenomena. The research continues under our new PAST grant, NNG04G131G beginning 5/1/2004. The original period of performance of the subject grant was 3/1/2001 to 2/28/2004, but was extended one year at no cost. Although there is some overlap in the scientific projects conducted during the extended year with those of the new grant, this report is confined to the portion of the work funded under NAG5-10435.

The primary goals for this grant period were a comparative study of outer planet thermospheres/ ionospheres near solar maximum, extended to the mid-IR, and the investigation of molecular dimers in outer solar system atmospheres. This project supports NASA's planned space missions, Jupiter Polar Orbiter, outer Planet Microprobes, and the recent Cassini flyby of Jupiter. It also supports the OSS strategic plan themes, The Exploration of the Solar System and The Sun-Earth Connection/ Understanding comparative planetary space environments.

Collaborators: Steve Miller (UCL), Sang J. Kim (Kyunghee), Tom R. Geballe (Gemini), John H. Lacy (U. Texas), and Dan F. Lester (U. Texas)

Observing runs

During 2001-2003, the PI participated in 8 observing runs to obtain data for this grant using the CoolSpec spectrograph at McDonald Observatory, the TEXES spectrograph, CSHELL, and SpeX at the Nasa Infrared Telescope Facility (IRTF) on Mauna Kea, and CGS4 at the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea. Jupiter, Saturn, Uranus, and Neptune were observed. In addition, data were obtained by collaborators on one 2002 observing proposal, in the PI's absence, to observe Jupiter's H_2^+ spectrum with SpeX at the IRTF. Mauna Kea proved to be a more effective site for infrared observing than McDonald Observatory owing to the higher altitude and resulting lower atmospheric water absorption and better seeing. Also, the light gathering power of the telescopes was greater than for the 2.7m telescope at McDonald Observatory.

TEXES and the Mid-IR

In addition to continuing our near-IR program, we began a program to study the mid-IR emission of the outer planets at high spectral resolution using TEXES, the University of Texas Echelle Spectrograph developed by John Lacy as a prototype for a SOPHIA instrument. TEXES observing was limited to only one or two observing runs a year because of the need to combine programs in order to reduce cryogen and logistics costs. Unlike the near-IR region, which reveals vibrational molecular bands, the mid-IR spectral region reveals many pure rotational bands. The rarefied atmospheres of the outer planets are heated both by solar EUV generally, exciting and ionizing H_2 , and the precipitation of magnetospherically trapped charged particles in auroral zones. The ion H_3^+ , formed by the reaction of H_2^+ with H_2 , is a major coolant governing the energy balance of the thermosphere and ionosphere. These species yield emission lines in the infrared which are accessible to ground based observation and study. The emission probes the effects that the solar EUV radiation causes in these upper atmospheres, including heating, energy balance, departures from thermal equilibrium, and physical processes such as aurorae, all as a function of the solar cycle and planetary season. Therefore, we undertook mid-IR observations of their pure rotational emission spectra to obtain the thermal heating in their auroral zones and to characterize their thermospheric/ ionospheric temperature structure in response to changing insolation. Solar maximum was at hand, with a solar EUV flux 2-3 times that at solar minimum, so we recorded phenomena near the time of extreme solar insolation. During this period, TEXES has proven that it can detect important features in outer planet atmospheres.

Research Results

Search for Pure Rotational H_2^+ Emission on Jupiter:

In collaboration with J. Lacy, we examined spectra of Jupiter taken on Feb 3 and 5, 2001, with TEXES at the IRTF in a search for the pure rotational emission lines of H_2^+ . Detection of H_3^+ would be useful for establishing the thermal response of Jupiter's ionosphere to auroral precipitation and Joule currents. However, this spectral region was found to exhibit many emission lines from atmospheric ethane, acetylene, or ethylene, and no rotational H_2^+ emission was detected.

First Ground-based Observations of Uranus' Pure-Rotational H_2 Spectrum:

Using TEXES at resolution $R=75,000$ on the IRTF to observe Uranus in the mid-IR, we detected for the first time spatially resolved emission of the planet's pure rotational S(1), S(2), and S(4) quadrupole emission lines of H_2 (The S(3) line was not observable because it was obscured by atmospheric ozone absorption). We detected the pure rotational S(4) quadrupole line of H_2 in emission on September 9, 2002. This is the first time this line has been detected in any planetary atmosphere. It complements our earlier detection of Uranus' H_2 S(1) and S(2) lines. The S(4) line will provide the necessary leverage for accurately assessing the temperature of Uranus' hot thermosphere. In particular, the spatial distribution of the intensity of these lines across the planet's disk will probe the vertical temperature distribution of the Uranian thermosphere to help answer the question, "Why is Uranus' thermosphere so hot?" Unlike observations of the near-IR H_2 vibrational quadrupole lines, these lines directly measure the thermal emission of H_2 . They arise from the hottest upper layers of Uranus' atmosphere and are important because they constrain models of Uranus' thermospheric structure and energy balance. These lines stand out in Uranus' spectrum because, unlike for Jupiter, the background hydrocarbon emission is negligible owing to Uranus' lower stratospheric temperature. We compared the equivalent widths of these lines with predictions from preliminary models of Uranus' thermosphere based on the Voyager UVS stellar/solar occultation thermal structures. The results constrain the thermal structure of Uranus' mid-thermosphere (Trafton, Lacy, Richter, & Greathouse 2003; Bull. Amer. Astron. Soc., 35, 1000).

Mutual Event Observations of Io's Sodium Corona:

Our collaborative work on this project was published (Burger et al. 2001; ApJ., 563, 1063-1074). At McDonald Observatory, we measured the column density profile of Io's sodium corona using mutual eclipses between the Galilean satellites. This approach circumvents the problem of spatially resolving Io's corona directly from Io's bright continuum in the presence of atmospheric seeing and telescopic scattering. The primary goal was to investigate the spatial and temporal variations of Io's corona. Spectra from the Keck Observatory and McDonald Observatory from ten 1997 events revealed a corona that is only approximately spherically symmetric around Io. Comparing the globally averaged radial sodium column density profile in the corona with profiles measured in 1991 and 1985, we found that there has been no significant variation. However, there appears to be a previously undetected asymmetry: the corona above Io's sub-Jupiter hemisphere is consistently denser than above the anti-Jupiter hemisphere.

The H_2 Dimer on Jupiter, Saturn, and Titan:

With S. J. Kim, Trafton analyzed spectra of the H_2 dimer they obtained at the UKIRT telescope of Jupiter, Saturn, and Titan. These spectral features are in the near-IR, around $2.1 \mu m$, and arise from the fundamental band of H_2 . They are useful indicators of the ortho- H_2 /para- H_2 ratio in the atmospheres of the giant planets because their line ratios are insensitive to the temperature, unlike the H_2 quadrupole lines. The ortho-/para- H_2 ratio is diagnostic of dynamical processes in these atmospheres. On Jupiter and Saturn, the strength of the H_2 dimer was found to vary with latitude in remarkable agreement with the CH_4 and background pressure-induced absorption; indicating a similar mixing ratio vs altitude. For Titan, they found evidence for a possible temporal variation of its absorption over a day, suggesting an abrupt weather/cloud change (see S. J. Kim, Trafton, Geballe, Lee, & J. H. Kim 2001; Bull. Amer. Astron. Soc., 33, 1044).

The H_2 Dimer on Uranus:

Trafton apparently detected the H_2 dimer features in spectra of Uranus coadded from several observing runs in order to build up the signal to noise ratio. These spectral features are in the near-IR, around $2.1 \mu m$, and arise from the fundamental band of H_2 . He had already detected these H_2 dimer features in the spectra of Jupiter, Saturn, and

Neptune; but strong absorption from the pressure-induced H_2 absorption in the clear Uranian atmosphere prevented previous detection. They are useful indicators of the ortho- H_2 /para- H_2 ratio in the atmospheres of the giant planets because their line ratios are insensitive to the temperature, unlike the H_2 quadrupole lines. The ortho-/para- H_2 ratio is diagnostic of dynamical processes in these atmospheres.

Modeling the Latitudinal Dependence of the H_2 Dimer on Jupiter and Saturn:

Also with S. J. Kim, Trafton analyzed the meridional 2 μm spectra of Jupiter and Saturn, which were observed in July, 1999 at the UKIRT telescope in collaboration with T. R. Geballe. The equivalent widths vs latitude of two prominent dimer absorption features near 2.122 μm were measured and compared with an ab-initio model of the $(H_2)_2$ dimer, constructed by modifying a quantum mechanical model of Schaefer and McKellar (1900: *Z. Phys. D-Atoms, Molecules and Clusters*, v. 15, p. 51) in order to extract the ortho-/para ratio of H_2 and its latitudinal variation, diagnostic of dynamical processes. [This work is currently being extended with more accurate quantum mechanical Calculations at Kyunghee.] (S. J. Kim, Trafton, Geballe, Lee, & J. H. Kim 2001; *Bull. Amer. Astron. Soc.*, 33, 1044).

Ion Winds in Saturn's Southern Auroral/Polar Region:

During February 6, 2003 at the IRTF using CSHELL, we measured the line-of-sight ionospheric wind velocity profile in the southern auroral/polar region of Saturn. This was derived from the measurement of the Doppler shift of the $H_2^+ v_2 Q(1,0-)$ line at 3.953 μm . The profiles are consistent with an extended region of the upper atmosphere sub-corotating with the planet: the ion velocities in the inertial reference are only 1/3 of those expected for full planetary corotation. We suggest that in this region of Saturn's ionosphere, Saturn's ion winds may be under solar wind control (Stallard, Miller, Trafton, Geballe, & Joseph 2004; *Icarus* 167, 204-211).

On the Jovian Near-IR Auroral H_2 Emission:

Jupiter's auroral cascade causes H_2 emission in the near-IR quadrupole lines, in addition to the FUV emission. Unlike the FUV aurora, the near-IR aurora can be observed from ground-based observatories; and has in fact been observed as emission in the H_2 (1-0) band in the spectra of Jupiter and Uranus (NASA SP-494, 229, 1989; *ApJ* 524, 1059, 1999). Unlike the near-IR H_2^+ aurora, which is formed by the reaction of H_2 ionized by the cascade reacting with neutral H_2 , the H_2 aurora can emit from atmospheric levels below the homopause, where H_2^+ would be destroyed by chemical reaction with hydrocarbons. H_2 thus probes the auroral energy input at deeper levels. We compared ground-based observations of Jupiter's auroral H_2 emission in the (1-0) Q-branch for various System III longitudes obtained during December 1999 and September 2000 using the CoolSpec Cassegrain IR spectrometer at the 2.7m telescope of the McDonald Observatory with decade-earlier spectra obtained with the since-retired Infrared Grating Spectrometer. We found an instance of a highly excited rotational temperature for H_2 on January 1, 1989 compared to anything seen recently. The $Q(3)/Q(1)$ line ratio was greater than unity, indicating a temperature in excess of 1800 K, compared to 900 K in 1999, assuming thermal equilibrium of the rotational levels - which is normally the case. However, the vibrational levels (only) of H_2 are known to routinely deviate from thermal equilibrium in Jupiter's aurorae; we confirmed significant non-equilibrium overpopulation of the $v=1$ level, due to the intensity of the auroral cascade (Trafton & Lester 2001; *Bull. Amer. Astron. Soc.*, 33, 1096).

Variable Aurorae and Thermospheric Emission on Uranus Near Solar Maximum:

Uranus is known to have a mild, localized aurora, which was first detected in its FUV spectrum but also is seen in its near-IR spectrum of H_2 and H_2^+ . In addition, solar EUV radiation is known to heat Uranus' upper atmosphere enough to produce emission in the fundamental-band H_2 quadrupole lines; and is primarily responsible for Uranus' ionosphere, which generates additional near-IR emission in the fundamental and overtone bands of H_2^+ . Since the solar wind and energetic particle output vary significantly over the solar cycle, a corresponding solar-cycle variation in Uranus' aurorae and ionospheric/ thermospheric emission spectrum is anticipated. We compared Uranus' near-IR emission spectrum, consisting of H_2^+ and quadrupole H_2 emission, obtained at the UKIRT telescope in September 2000 approaching solar maximum and July 2002 just after solar maximum with observations obtained in June 1995 approaching solar minimum. Uranus' emission was found to be substantially weaker during September 2000. Although the emission for both species during July 2002 was observed to be comparable to or brighter than the emission near solar minimum, the emission during June 2001 was found to be weaker than either, by approximately a factor of two. This difference indicates that there are other factors that govern the state of Uranus' upper atmosphere than just the solar input (Trafton, Miller, & Geballe 2002; Talk presented to the meeting, *Magnetospheres of the Outer Planets* held July 29 - Aug 2, at the Applied Physics Lab, Johns Hopkins University).

A Second Prominent Hot-Spot Event for Uranus' Thermosphere:

During an observing run at the IRTF/SpeX on July 21, 2002, which was near solar maximum, we observed an enhancement of the rotational temperature of Uranus' upper-atmospheric H₂ based on the near-IR spectroscopic Q-branch emission at 2.42 μ m. This appears to be the second detection of an unusually hot-emission event: The first was on May 4, 1993 when the temperature exceeded 950 K. This compares to an average temperature of 624 \pm 24 K determined in 1995, near solar minimum. The 2002 event reached 1040 K compared to the run-average of 670 K. Both the intensity and temperature were elevated significantly compared to other observations made during the 1992-1995 period. It was suggested then (Trafton et al. 1999; ApJ 524, 1059) that this may have been a detection of Uranus' aurora passing through the spectroscopic slit, against the global background of thermal emission from the hot thermosphere. Owing to the large sub-Earth latitude then (-56 deg) and the low latitude of Uranus' fragmented auroral arc (due to the 60 deg tilt of the offset magnetic pole), aurorae should have occurred close to the limb and have been enhanced by the secant path. Unlike the first event, however, Uranus' sub-Earth latitude was only -20 deg so that a detected aurora would not lie close to the limb, or be significantly enhanced by the secant. For this event, the pixel size was much smaller (0."15 square vs 3"x3" before), allowing the emission to be resolved spatially on Uranus' disk. The most likely cause is either a planetary aurora or an interaction between Uranus' ionosphere and incident solar energetic particles released by a solar flare or coronal mass ejection event near the current solar maximum. Such interaction is possible owing to the steep inclination of Uranus' magnetic pole, which periodically points towards the Sun during the planet's rotation (Trafton, Miller, & Geballe 2002; Bull. Amer. Astron. Soc., 34, 905-906).

Publications

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- "Io Observations from the Ground and with HST/STIS", L. M. Trafton, In *Astronomical Instrumentation and the Birth and Growth of Astrophysics: A Symposium held in honor of Robert G. Tull*, (eds. F. Bash & C. Sneden), ASP Conference Series, Vol. 270, 63-70, 2002.
- "Ion Winds in Saturn's Southern Auroral/Polar Region", T. S. Stallard, S. Miller, L. M. Trafton, T. R. Geballe, & R. D. Joseph, Icarus 167, 204-211.
- "Jupiter's Near-IR Auroral H₂ Emission", L. M. Trafton & D. F. Lester, presented at the meeting, "*Jupiter: The Planet, Satellites & Magnetosphere*" held in boulder, CO, June 25-30, 2001.
- "Latitudinal Variations of the 2 μ m Absorption Features of (H₂)₂ Dimers in the Atmospheres of Jupiter and Saturn", S. J. Kim, L. M. Trafton, T. R. Geballe, Y. S. Lee, & J. H. Kim, Bull. Amer. Astron. Soc., 33, 1044; 2001.
- "On the Jovian Near-IR Auroral H₂ Emission, L. M. Trafton & D. F. Lester, Bull. Amer. Astron. Soc., 33, 1096; 2001.
- "Search for Enhanced Aurora and Episodic Ionospheric/ Thermospheric Emission on Uranus During Solar Maximum", L. M. Trafton, S. Miller, & T. R. Geballe, presented at the meeting, *Magnetospheres of the Outer Planets* held July 29 - Aug 2, 2002, at the Applied Physics Lab, Johns Hopkins University.
- "A Second Prominent Hot-Spot Event for Uranus' Thermosphere", L. M. Trafton, S. Miller, & T. R. Geballe, Bull. Amer. Astron. Soc., 34, 905-906; 2002.
- "Observations of Uranus' Pure-Rotational H₂ Quadrupole Lines", L. M. Trafton, J. H. Lacy, M. Richter, & T. K. Greathouse, Bull. Amer. Astron. Soc., 35, 1000; 2003.